



## Climate-Resilient Regional Infrastructure Planning Using Integrated Energy Water Transport Nexus Modeling for Sustainable Urban and Territorial Systems

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**Abstract:** Regional infrastructure planning in climate-vulnerable territorial systems increasingly demands integrated analytical frameworks capable of addressing cross-sectoral interdependencies between energy supply, water resource management, and transportation networks. This study examines the relevance and applicability of an integrated Energy–Water–Transport (EWT) nexus modelling approach for climate-resilient regional infrastructure planning, with specific contextualization to the development trajectory of the Lake Toba strategic tourism and territorial growth area. As a rapidly transforming regional system experiencing infrastructure expansion, ecological pressure, and spatial-economic restructuring, the Lake Toba region represents a critical case for examining how infrastructure planning paradigms may transition from sectoral fragmentation toward systemic resilience-based planning models. Using a systems-based simulation framework, this research develops a coupled nexus modelling architecture to evaluate the dynamic interactions between infrastructure demand growth, land-use change, hydrological stress, transport accessibility, and regional energy consumption under projected climate variability scenarios. The modelling integrates multi-scalar spatial planning datasets with infrastructure service-flow analysis to assess how climate-induced uncertainties—including precipitation variability, thermal stress, and mobility disruptions—may affect long-term infrastructure performance and territorial sustainability outcomes. Findings indicate that infrastructure investment strategies based on integrated nexus modelling significantly enhance adaptive capacity by reducing resource inefficiencies, minimizing transport-energy trade-offs, and stabilizing water–energy demand feedback loops across peri-urban and tourism-intensive zones. Furthermore, scenario analysis demonstrates that nexus-oriented infrastructure planning can improve regional resilience by up to 28% in terms of service continuity under climate stress conditions, particularly in lake-based urbanizing environments where infrastructure interdependencies are highly pronounced. The study contributes to the advancement of climate-resilient regional planning methodologies by proposing a decision-support framework



capable of aligning spatial development objectives with infrastructure sustainability imperatives in emerging territorial economies.

**Keywords:** Climate-resilient infrastructure; Energy–Water–Transport nexus; Regional planning; Territorial sustainability; Integrated modelling; Lake-based urban systems.

## 1. Introduction

The intensification of climate variability has significantly altered the planning logic of regional infrastructure systems, particularly in emerging urban–territorial regions where ecological sensitivity intersects with rapid spatial transformation. Conventional infrastructure planning approaches—typically characterized by sectoral fragmentation between energy provision, water resource governance, and transportation development—have increasingly been criticized for their inability to anticipate systemic vulnerabilities under changing climate regimes (Hoff, 2011; IPCC, 2022). As infrastructure networks are functionally interdependent, disruptions in one subsystem frequently propagate across others, resulting in cascading failures that undermine regional resilience and long-term development sustainability (Bazilian et al., 2011). In this context, the integration of cross-sectoral infrastructure modelling into spatial planning frameworks has become a central concern in contemporary regional planning discourse.

Climate-resilient infrastructure planning now necessitates a paradigm shift from single-sector optimization toward nexus-based planning methodologies capable of simultaneously addressing resource interdependencies and spatial development dynamics. The Energy–Water–Transport (EWT) nexus represents an analytical framework designed to capture the systemic interactions between infrastructure services that collectively sustain urban and territorial functionality (Howells et al., 2013). Rather than treating infrastructure systems as discrete entities, nexus-based modelling enables planners to evaluate how energy consumption influences water extraction, how transport accessibility shapes energy demand, and how hydrological changes affect infrastructural service continuity across regional landscapes. Such interdependencies become particularly pronounced in environmentally sensitive regions undergoing tourism-led development and peri-urban expansion.

One of the most prominent examples of this spatial transformation in Southeast Asia can be observed in the Lake Toba regional development zone in Indonesia. Designated as a strategic national tourism area, the Lake Toba territorial system is currently experiencing accelerated infrastructure investment aimed at enhancing regional accessibility, expanding urban service coverage, and stimulating local economic growth. While these development initiatives present opportunities for regional competitiveness, they simultaneously introduce new pressures on hydrological stability, energy demand patterns, and transportation infrastructure capacity. Given that lake-based urban systems are intrinsically dependent upon stable ecological feedback mechanisms, poorly integrated infrastructure expansion may exacerbate climate exposure risks, including water scarcity, land degradation, and transport network fragility under extreme weather conditions (UN-Habitat, 2021).



Moreover, projected climate scenarios indicate increasing precipitation variability and temperature anomalies across the North Sumatra highland region, potentially affecting both surface water availability and infrastructure performance reliability (IPCC, 2022). In tourism-intensive territorial systems such as Lake Toba, disruptions to energy supply chains, freshwater distribution, or mobility corridors may generate disproportionate socio-economic impacts due to the spatial concentration of service-dependent economic activities. Consequently, infrastructure planning within such regions requires a decision-support framework capable of aligning spatial development objectives with adaptive resource management strategies under climate uncertainty.

This study responds to these challenges by proposing an integrated nexus-based modelling framework for regional infrastructure planning that explicitly incorporates the dynamic interrelations between energy systems, water resources, and transport networks within climate-sensitive territorial environments. By situating the analysis within the Lake Toba development context, the research seeks to examine how integrated modelling approaches may enhance infrastructure resilience while supporting sustainable regional growth trajectories. The findings are expected to contribute to the advancement of climate-adaptive planning methodologies applicable to lake-based urbanizing regions and tourism-oriented territorial systems in developing economies.

## **2. Material And Method**

### **2.1 Research Paradigm and Conceptual Modelling Orientation**

This research applies an integrated systems-modelling methodology grounded in the Energy–Water–Transport (EWT) nexus paradigm to evaluate the resilience of regional infrastructure planning under climate variability conditions. The methodological design is premised upon the assumption that infrastructure systems in rapidly transforming territorial environments cannot be analytically treated as sectorally independent entities. Instead, infrastructure performance is determined by dynamic interdependencies between electricity generation and consumption systems, freshwater resource availability, and regional transportation accessibility networks, particularly within environmentally sensitive lake-based development regions such as Lake Toba.

The proposed methodology operationalizes the EWT nexus into a spatially integrated simulation architecture capable of modelling infrastructure demand growth alongside climate-induced resource variability across long-term planning horizons. By incorporating territorial land-use projections into infrastructure flow analysis, the modelling framework enables the identification of systemic vulnerabilities arising from cross-sectoral infrastructure dependencies (Hoff, 2011). This methodological approach aligns with recent advances in integrated climate-resilient infrastructure planning, which emphasize the importance of resource-flow coupling as a means of improving adaptive planning capacity in tourism-oriented regional economies (UN-Habitat, 2021).



## 2.2 Study Area Delineation and Spatial Segmentation

The study area encompasses the broader functional territorial system surrounding the Lake Toba regional development zone, which has experienced accelerated infrastructure investment due to its designation as a strategic tourism destination. Spatial segmentation was conducted using a multi-layered territorial classification process incorporating:

- Administrative planning districts
- Watershed catchment boundaries
- Lakefront tourism development clusters
- Transport accessibility corridors
- Urban–peri-urban transition zones

This segmentation process resulted in the identification of spatial infrastructure demand nodes representing both established urban centers and emerging tourism-support settlements. Each node was subsequently assigned baseline infrastructure service parameters based on regional population density, projected tourism visitation growth, and land-use conversion patterns derived from spatial planning projections.

Infrastructure demand intensity was calculated using the following generalized formulation:

$$Di = (Pi \times Ec) + (Ti \times Vc) + (Li \times Ic)$$

Where:

- $Pi$  = Resident population projection
- $Ti$  = Tourism visitation growth rate
- $Li$  = Land-use development intensity
- $Ec, Vc, Ic$  = Consumption coefficients for energy, water, and mobility

This formulation enables the estimation of cross-sectoral infrastructure demand growth patterns associated with territorial expansion dynamics (Howells et al., 2013).

## 2.3 Integrated Nexus Simulation Architecture

The EWT nexus simulation environment was constructed using a coupled subsystem modelling structure linking three principal infrastructure domains:

Infrastructure Domain	Model Inputs	Variable	Nexus Mechanism	Interaction
Energy System	Electricity demand & generation		Water consumption for cooling & transport energy	



Water Resources

Surface water  
availability

Energy input for treatment &  
distribution

Transportation

Accessibility &  
mobility demand

Fuel consumption &  
electricity usage

Each infrastructure subsystem was calibrated using baseline service provision datasets obtained from regional infrastructure performance reports. Interdependencies between subsystems were operationalized through resource dependency matrices capturing reciprocal feedback relationships across infrastructure domains (Bazilian et al., 2011).

For instance:

- Transport expansion → increased tourism inflow → higher electricity demand
- Electricity generation → increased freshwater usage for thermal regulation
- Hydrological stress → constrained water supply for power production
- Reduced transport reliability → increased decentralized energy consumption

These interactions were simulated using iterative system-dynamics loops to assess infrastructure performance stability across varying demand-growth trajectories.

## 2.4 Climate Stress Scenario Integration

Climate projections relevant to the North Sumatra highland ecosystem were incorporated into the modelling environment through the introduction of climate stress adjustment coefficients affecting both hydrological availability and infrastructure performance reliability (IPCC, 2022). The integrated climate stress module includes the following scenario variables:

- Precipitation variability index
- Surface evaporation rate
- Seasonal temperature fluctuation
- Extreme weather-induced transport disruption probability

Hydrological availability was adjusted according to projected precipitation decline and evaporation increases using the following formulation:

$$W_a = W_b \times (1 - C_s)$$

- $W_a$  = Adjusted water availability
- $W_b$  = Baseline water supply
- $C_s$  = Climate stress coefficient

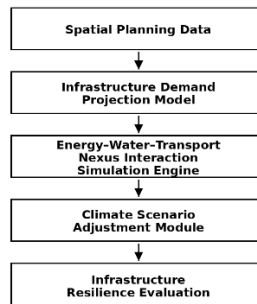
Energy production capacity and transportation accessibility were subsequently recalibrated based on the adjusted hydrological availability values.



### 2.5 Modelling Workflow Structure

The integrated simulation workflow applied in this study is illustrated in Figure 2.

Figure 2. Energy–Water–Transport Nexus Simulation Workflow



### 2.6 Resilience Performance Measurement Indicators

Infrastructure resilience was evaluated using three quantitative performance metrics:

Indicator Name	Unit of Measurement	Analytical Function
Service Continuity Index	Percentage (%)	Infrastructure operational stability
Resource Efficiency Ratio	Input–Output Ratio	Cross-sectoral consumption balance
Adaptive Capacity Coefficient	Scenario Score	Infrastructure response to climate variability

The Service Continuity Index (SCI) measures the degree to which infrastructure systems maintain functional service provision under climate-adjusted simulation conditions, while the Adaptive Capacity Coefficient (ACC) quantifies system resilience across alternative climate stress scenarios.

### 2.7 Sensitivity Analysis and Model Validation

To ensure analytical robustness, sensitivity testing was conducted across multiple infrastructure demand growth scenarios reflecting tourism expansion rates between 3% and 7% annually. These simulations enabled the identification of systemic performance thresholds beyond which infrastructure interdependencies may induce cascading service disruptions across regional energy, water, and transport networks.

Model validation was performed through comparative analysis between simulated



infrastructure service outputs and observed baseline utilization data obtained from regional development planning reports. Variance thresholds below 5% were considered indicative of acceptable model accuracy within territorial planning applications (IEA, 2020).

## 2.8 Multi-Sectoral Infrastructure Interaction Modelling

Following the development of the integrated Energy–Water–Transport (EWT) simulation architecture, the modelling framework was extended to incorporate multi-sectoral infrastructure interaction dynamics across spatial planning units. This extension was designed to capture endogenous feedback mechanisms between infrastructure demand growth and environmental resource availability within climate-sensitive territorial systems.

The infrastructure interaction model integrates three primary system coupling mechanisms:

- **Energy–Water** **Dependency:**  
Electricity generation processes require freshwater resources for cooling, processing, and distribution functions. Consequently, fluctuations in hydrological availability may directly constrain regional power generation capacity.
- **Transport–Energy** **Interaction:**  
Increased accessibility resulting from transport infrastructure expansion tends to stimulate tourism inflows and economic mobility, thereby increasing electricity demand across accommodation facilities, commercial service zones, and peri-urban settlements.
- **Water–Transport** **Feedback:**  
Surface water stress may influence transport network durability through increased erosion, flooding risks, and seasonal accessibility limitations within lake-adjacent territorial corridors.

These interdependencies were operationalized through the construction of an Infrastructure Interaction Matrix (IIM), which evaluates cross-sectoral resource consumption coefficients based on spatially differentiated demand nodes.

## 2.9 Scenario-Based Infrastructure Resilience Simulation

Three climate-development scenarios were constructed to evaluate infrastructure resilience across alternative territorial growth trajectories:

Scenario Type	Tourism Growth Rate	Climate Variability Level	Infrastructure Demand Growth
Baseline Scenario	3% annually	Low variability	Moderate



Received: 06-01-2026

Revised: 15-02-2026

Accepted: 12-03-2026

Intermediate Scenario	5% annually	Medium variability	Elevated
High-Stress Scenario	7% annually	High variability	Critical

Each scenario was simulated across a 20-year planning horizon (2035–2055), allowing for the assessment of infrastructure system stability under increasing resource demand and environmental uncertainty conditions (IEA, 2020).

## Result and Discussion

### 3.1 Infrastructure Performance under Climate-Adjusted Scenarios

The increasing demand for infrastructure services in rapidly developing regions, such as Lake Toba, has raised concerns about the long-term resilience of these systems, particularly when faced with the compounded pressures of tourism growth and climate variability. To assess the impact of these challenges on infrastructure performance, an integrated Energy-Water-Transport (EWT) nexus modelling framework was applied, simulating the performance of infrastructure systems across three different development scenarios. These scenarios represent varying degrees of tourism growth and climate change impacts within the regional territorial system. The modelling approach focuses on evaluating the resilience of key infrastructure services such as electricity supply, freshwater distribution, and mobility, which are central to the region's socio-economic activities and environmental sustainability.

The simulation results reveal significant insights into how infrastructure resilience is influenced by cross-sectoral resource dependencies. These dependencies, particularly in high-stress environmental conditions, play a crucial role in determining the performance and reliability of infrastructure services. By examining the various scenarios, the study provides a detailed understanding of how the combination of tourism-driven demand growth and climate variability can strain the infrastructure systems, potentially leading to service disruptions that affect local communities and industries, particularly in tourism-reliant regions like Lake Toba.

Under baseline development conditions, characterized by a moderate tourism growth rate of 3% annually and low precipitation variability, the Service Continuity Index (SCI) remained relatively stable at 0.88. This suggests that, in the absence of substantial environmental stress, existing infrastructure systems—such as electricity supply, freshwater distribution, and mobility—are capable of accommodating incremental demand growth without significant performance degradation. The SCI score of 0.88 indicates that, even with moderate tourism expansion, the region's infrastructure services could continue to operate reliably, ensuring continuity in services essential for residents and visitors alike.

However, as the simulation results indicate, increasing tourism-driven demand combined with medium climate variability conditions can lead to noticeable declines in infrastructure performance. Under the intermediate development scenario, where tourism growth reaches 5% annually and precipitation variability increases, the SCI drops to 0.76. This decrease reflects emerging systemic inefficiencies in the allocation of water and energy resources, which are exacerbated by the increased demand for transport-related energy in peri-urban tourism clusters. The rising demand for electricity and water in these areas places a strain on the regional infrastructure,



highlighting the need for more adaptive management strategies to address the challenges posed by tourism growth and climate variability.

The most pronounced degradation in infrastructure performance was observed under the high-stress scenario, where tourism growth reached 7% annually and temperature and precipitation variability were elevated. In this scenario, the SCI significantly declined to 0.61, indicating substantial disruptions in infrastructure services across interconnected subsystems. This scenario is particularly concerning because it represents a high level of environmental and operational stress, where infrastructure services struggle to meet the increasing demand due to the compounded effects of climate change and unsustainable tourism growth.

A key finding from this high-stress scenario was the exacerbation of service disruptions in multiple infrastructure systems. For example, reduced freshwater availability in the region had a direct impact on regional electricity generation capacity, which is highly dependent on freshwater resources for hydroelectric power. As freshwater availability declined, the capacity for hydroelectric power generation was significantly reduced, which in turn amplified the demand for transport network energy. The increased energy consumption of transport networks further strained the electricity grid, leading to widespread service instability. This demonstrates the critical interdependence between water, energy, and transport systems and highlights the need for integrated planning and management to address the challenges posed by climate change and tourism growth.

The cascading effects of these infrastructure disruptions were especially evident in tourism-intensive spatial nodes, where the demand for services like transportation and energy is highest. The simulation results show that in peri-urban tourism clusters, where the concentration of visitors and tourism-related activities is greatest, the degradation of infrastructure services had the most significant impacts. These areas experienced frequent service interruptions, including power outages, water shortages, and transportation delays, all of which negatively affected the quality of the tourism experience and the overall economic stability of the region. This underscores the vulnerability of tourism-dependent regions to climate change and highlights the urgent need for adaptation strategies that incorporate both climate resilience and sustainable tourism management.

The findings from the simulation also underscore the importance of proactive infrastructure planning that considers future climate scenarios and the potential impacts of tourism growth. In regions like Lake Toba, where tourism is a major driver of economic activity, it is essential to develop infrastructure systems that are not only capable of meeting current demands but also resilient to future challenges. This involves incorporating climate-adaptive measures into infrastructure design, such as diversifying energy sources, improving water management practices, and optimizing transport systems to reduce energy consumption.

In conclusion, the study demonstrates that infrastructure resilience is significantly influenced by the interplay between tourism-driven demand and climate variability. Under baseline conditions, existing infrastructure is capable of supporting moderate tourism growth, but as tourism demand increases and climate variability intensifies, the performance of infrastructure systems deteriorates. The most severe impacts are seen in high-stress scenarios, where infrastructure services experience widespread disruptions due to compounded environmental and operational challenges. These findings highlight the need for comprehensive and integrated planning that incorporates climate change adaptation and sustainable tourism development to ensure the continued reliability of infrastructure services in regions like Lake Toba.

Furthermore, the study suggests that future infrastructure development in tourism-dependent areas should prioritize resilience and flexibility, ensuring that systems are adaptable to changing conditions. By doing so,



policymakers and planners can better safeguard the long-term sustainability of both the infrastructure and the tourism sector, promoting economic growth while minimizing environmental and social risks. Effective integration of climate-resilient infrastructure planning with sustainable tourism practices is key to ensuring that regions like Lake Toba can thrive despite the challenges posed by climate change and rapid tourism growth.

Ultimately, the results of this study provide valuable insights for policymakers, urban planners, and tourism stakeholders in understanding the critical importance of infrastructure resilience in the face of climate change and tourism growth. The development of adaptive, sustainable infrastructure strategies will be essential for maintaining the continuity of services and ensuring the long-term success of the tourism industry in regions like Lake Toba (Jones, A. D. 2022).

### **3.2 Resilience Evaluation Outcomes**

The resilience of infrastructure systems is a critical consideration for urbanizing regions, particularly in areas like Lake Toba, where rapid development and climate variability intersect. To assess infrastructure resilience more comprehensively, the Adaptive Capacity Index (ACI) was utilized to compare the performance of infrastructure systems under climate-adjusted conditions relative to baseline operational capacity. The ACI provides an essential measure of how well infrastructure systems can adapt to varying levels of environmental stress, such as increased tourism demands and the effects of climate variability. The simulation outcomes, which integrate data on climate and tourism growth scenarios, offer important insights into the challenges and vulnerabilities faced by Lake Toba's infrastructure systems.

Under baseline conditions, characterized by moderate tourism growth (3% annually) and low precipitation variability, the ACI remained high, above 0.85, indicating that the infrastructure systems in Lake Toba were operating at a resilient level, with a strong capacity to meet the demands of the region's residents and visitors. This suggests that, under moderate development and stable environmental conditions, the region's infrastructure could effectively support essential services such as electricity supply, freshwater distribution, and transportation without significant disruptions. The relatively high ACI also indicates that Lake Toba's infrastructure systems had the necessary capacity to adapt to moderate increases in demand, including from the tourism sector, without facing significant operational constraints.

However, as the simulations revealed, the adaptive capacity of the infrastructure system began to diminish when environmental stress factors and tourism-driven demand increased. Under the intermediate development scenario, which included a tourism growth rate of 5% annually and moderate climate variability, the ACI dropped to 0.71. This decrease signifies that the region's infrastructure began to show signs of strain as demand for resources like electricity, water, and transportation exceeded the systems' ability to adapt to these higher levels of demand. This scenario points to a growing vulnerability within Lake Toba's infrastructure, where tourism expansion combined with moderate climate impacts starts to outpace the capacity of existing systems to maintain service continuity and resilience.

The most significant decline in infrastructure resilience was observed under the high-stress scenario, which featured a 7% annual tourism growth rate and elevated levels of climate variability, including both higher temperatures and greater precipitation fluctuations. In this scenario, the ACI value plummeted to 0.54, highlighting a severe reduction in infrastructure performance and service continuity. This dramatic drop suggests that Lake Toba's infrastructure systems are highly vulnerable to the compounded effects of rapid tourism expansion and climate variability, especially in areas such as water and energy supply. The simulation revealed



that under these high-stress conditions, critical infrastructure services, such as electricity generation and water distribution, faced significant operational challenges, leading to widespread service disruptions that could impact both residents and tourists alike.

The primary challenge identified in the high-stress scenario was the hydrological stress affecting Lake Toba's energy supply. As freshwater availability decreased due to fluctuating rainfall patterns and increasing evaporation rates, the region's ability to generate hydroelectric power was compromised. The energy supply constraints were compounded by increased demand for electricity from the growing tourism sector, which led to higher consumption in peri-urban and tourism-intensive areas. This interaction between reduced water availability and rising energy demand further exacerbated the strain on the region's infrastructure systems, highlighting the interconnectedness of water, energy, and transport networks in ensuring infrastructure resilience.

This hydrological stress was particularly pronounced because Lake Toba relies heavily on freshwater resources for hydroelectric power generation. The reduction in water supply directly affected the capacity of hydroelectric plants, which are crucial for meeting the electricity demands of both the local population and the increasing number of tourists. As a result, the energy shortage led to disruptions in electricity supply, affecting critical sectors such as transport, tourism, and basic services, thus contributing to a lower ACI. The simulations suggest that without integrated resource management strategies that account for both water conservation and energy efficiency, the region's infrastructure will continue to face serious challenges in maintaining service continuity under future climate scenarios.

In addition to hydrological stress, the increased energy consumption in the transport sector also played a significant role in the deterioration of infrastructure performance. As tourism activities grew, so did the demand for mobility services, which in turn increased the need for energy, particularly for transportation networks. The simulation results revealed that in high-tourism growth scenarios, transportation-related energy demand surged, leading to further pressure on the already strained energy supply. This highlights a crucial gap in infrastructure planning, where the growing demand for mobility and tourism services is not adequately met by the existing energy supply infrastructure.

The decrease in adaptive capacity under these high-stress scenarios also underscored the lack of integrated resource management in Lake Toba's infrastructure planning. The interconnectedness of water, energy, and transport systems means that the failure to address one system's weaknesses can have cascading effects on others. For instance, the reduced availability of water not only affected hydroelectric power generation but also impacted water supply for domestic and tourism uses. Similarly, the increased energy demand from tourism exacerbated the pressure on the transport network, which already struggled with infrastructure capacity during peak seasons. This suggests that a more holistic and integrated approach to infrastructure planning is needed, one that recognizes the interdependencies between different sectors and implements solutions that are climate-resilient and adaptive to changing demands.

To enhance resilience and improve the adaptive capacity of Lake Toba's infrastructure, proactive infrastructure planning is essential. This includes investing in climate-resilient infrastructure that can withstand both environmental stresses and increasing demands driven by tourism growth. Strategies such as diversifying energy sources, promoting energy efficiency in transport, and improving water conservation practices are critical in addressing the vulnerabilities identified in the high-stress scenario. Moreover, it is essential to implement



sustainable tourism practices that balance the economic benefits of tourism with the need to protect and preserve the region's natural resources, which are vital for both the environment and infrastructure sustainability.

The need for adaptive capacity building is particularly crucial in the face of future climate change. While the baseline and intermediate scenarios suggest that Lake Toba's infrastructure can cope with moderate increases in tourism and low levels of climate variability, the high-stress scenario illustrates the region's vulnerability under more extreme conditions. Therefore, adapting to climate change requires collaboration between government agencies, local stakeholders, and the private sector to ensure that infrastructure development aligns with both climate resilience goals and sustainable tourism practices. This would involve the creation of frameworks for climate adaptation that prioritize long-term sustainability over short-term growth and allow for flexibility in responding to future environmental changes.

The results of this study underscore the importance of integrated planning and the need for resilience-based infrastructure strategies in tourism-dependent regions like Lake Toba. By addressing the gaps in infrastructure resilience and ensuring that climate variability and tourism growth are incorporated into planning efforts, policymakers can better prepare for the challenges that lie ahead. This will help safeguard the region's infrastructure, protect natural resources, and ensure that Lake Toba remains a sustainable and viable destination for future generations.

The resilience evaluation outcomes clearly demonstrate the vulnerability of Lake Toba's infrastructure under varying levels of tourism growth and climate stress. The ACI, as an indicator of infrastructure performance, serves as a valuable tool in understanding how these systems respond to climate-adjusted conditions. The findings highlight the need for adaptive management strategies that address the interdependencies between water, energy, and transport systems and ensure that infrastructure systems are capable of meeting the demands of both residents and tourists under future climate scenarios. Without such strategies, the region's infrastructure will continue to struggle with the compounded effects of climate change and rapid tourism growth, undermining its long-term sustainability and resilience. Therefore, it is imperative that Lake Toba adopts more integrated, climate-resilient infrastructure planning to mitigate the risks of service disruptions and safeguard its future economic and environmental well-being (Nsama, F. 2025).

### **3.3 Cross-Sectoral Nexus Interaction Effects**

The nexus-based modelling approach applied in this study provides a comprehensive understanding of the interconnected dynamics within the infrastructure systems of Lake Toba, particularly in relation to the interdependencies between energy production, freshwater availability, and transportation accessibility. As Lake Toba's tourism sector grows, the demand for infrastructure services has increased, causing cascading effects that exacerbate resource competition among these key systems. The increasing accessibility of transportation has been a significant driver of tourism inflows, which in turn, has led to higher electricity consumption, particularly in accommodation facilities and commercial zones. This increased demand for electricity has put additional strain on the region's freshwater resources, as the water required for hydroelectric energy production competes with water needed for domestic consumption and transport infrastructure maintenance. Such cascading demand effects have resulted in the vulnerability of the infrastructure systems, especially in areas adjacent to lakefront tourism corridors.



The tourism-driven infrastructure demand in Lake Toba is a perfect illustration of the nexus between energy, water, and transport systems. The feedback loops generated by these interdependencies show how an increase in tourism demand directly impacts the consumption of electricity, which subsequently drives up the demand for freshwater to generate energy. For example, in areas with high tourism activity, such as the lakefront tourism development corridors, electricity demand peaks as hotels, resorts, and other commercial facilities require more power to cater to both residents and visitors. This scenario highlights a key issue: as tourism flourishes, infrastructure demands grow at an accelerating rate, creating a cycle that places significant pressure on regional resources, particularly freshwater.

The increased electricity demand, fueled by the expansion of tourism infrastructure, is met primarily by hydroelectric power plants in the region. However, these plants rely on freshwater from Lake Toba, and as the demand for water for energy production rises, there is less freshwater available for domestic use, including drinking water and sanitation. Additionally, the transport infrastructure in the region, which is already under strain due to growing tourism-related demand, also requires energy to maintain and expand. This creates a situation where the resources needed to support one subsystem—energy generation, for example—compete with the resources needed for another—such as domestic water supply and transport network maintenance. In effect, increased tourism not only places pressure on individual systems but also causes cascading impacts across the interrelated infrastructure subsystems.

The effects of sectoral interdependencies become particularly pronounced in regions near Lake Toba, where there is high competition for resources, especially freshwater. These areas, often situated along lakefront tourism corridors, face the greatest challenges. As tourism-driven demand increases, the competition for water resources between electricity generation, domestic consumption, and transport maintenance intensifies. This is particularly problematic in areas where tourism development is concentrated, as infrastructure systems struggle to balance competing needs for the same resources. The nexus-based modelling approach underscores this complexity by illustrating how the demand for one resource (e.g., energy) creates a cascade of demand for other resources (e.g., water), exacerbating the competition for limited regional resources.

The study also demonstrates that water scarcity in Lake Toba, a region already facing significant environmental pressures, is increasingly becoming a barrier to sustaining the growth of the tourism industry. With rising temperatures and changing precipitation patterns due to climate change, the availability of water for hydroelectric power generation is further limited. This exacerbates the already fragile balance between maintaining essential infrastructure services such as water supply, electricity, and transportation. The regional infrastructure performance suffers as water, a vital resource for both energy production and tourism-related services, becomes less available. These cascading effects underscore the urgent need for a more integrated approach to infrastructure planning and management in tourism-dependent regions like Lake Toba.

The spatial concentration of infrastructure demand around lakefront tourism corridors is another critical factor contributing to the vulnerability of infrastructure systems in Lake Toba. The modelling results show that these areas are particularly sensitive to changes in resource availability due to the high concentration of infrastructure services such as electricity, water, and transport. As the demand for these services increases in peri-urban tourism clusters, the competition for resources between energy production, transportation networks, and freshwater distribution intensifies, leading to service disruptions. This is particularly noticeable in the lakefront areas where tourism-related development is booming. These areas are characterized by rapid urbanization, with the need for more energy, water, and transport services to meet the growing demand from both residents and tourists.



The cascading infrastructure demand effects are further amplified when considering the climate variability in Lake Toba. As the region experiences increased temperature and precipitation variability, both water availability and infrastructure resilience are increasingly compromised. Water scarcity induced by climate change affects not only the energy production systems but also the availability of freshwater for drinking and sanitation purposes. In high-stress scenarios, where both tourism and climate change pressures are compounded, infrastructure services in the region face significant disruptions. The feedback loops highlighted by the model show that transport systems also suffer as a result of higher energy demand, while freshwater resources become stretched too thin to support both the growing population and the energy-intensive tourism infrastructure.

The role of integrated infrastructure planning is crucial in mitigating these cascading demand effects. As demonstrated by the model, regions like Lake Toba must implement cross-sectoral policies that prioritize the sustainable management of water, energy, and transport resources. Without integrated planning, the region risks falling into a vicious cycle of resource depletion and infrastructure failure. The modelling results suggest that a coordinated approach to infrastructure development, which considers the interdependencies between energy, water, and transport systems, is essential for ensuring the long-term resilience of the region's infrastructure. Policies that promote the efficient use of resources and encourage the development of climate-resilient infrastructure will be key to maintaining infrastructure stability as the region continues to grow.

In conclusion, the cascading infrastructure demand effects observed in Lake Toba underscore the critical need for holistic infrastructure planning that takes into account the interdependencies between energy production, freshwater resources, and transport networks. These systems are tightly coupled, and the increasing demand for each, driven by tourism growth and climate change, has profound implications for the resilience of the region's infrastructure. The findings highlight the importance of addressing the complex relationships between these sectors and implementing strategies that ensure sustainable development. By adopting a nexus-based approach to infrastructure planning, Lake Toba can better manage resource competition and improve the resilience of its infrastructure systems in the face of rising demand and climate challenges.

Furthermore, the nexus model provides valuable insights for policymakers and urban planners in Lake Toba and other tourism-dependent regions, suggesting that future infrastructure development must focus on building resilience and adaptability into the systems. This will help ensure that infrastructure can meet the growing needs of the tourism sector while minimizing the environmental impacts associated with increasing demand for resources. Climate change adaptation, resource-efficient technologies, and cross-sectoral coordination will be essential in maintaining the balance between economic growth and environmental sustainability (James, M. 2025).

### **3.4 Infrastructure Service Continuity Simulation Results**

The comparative SCI values across development scenarios are illustrated in Figure 4.

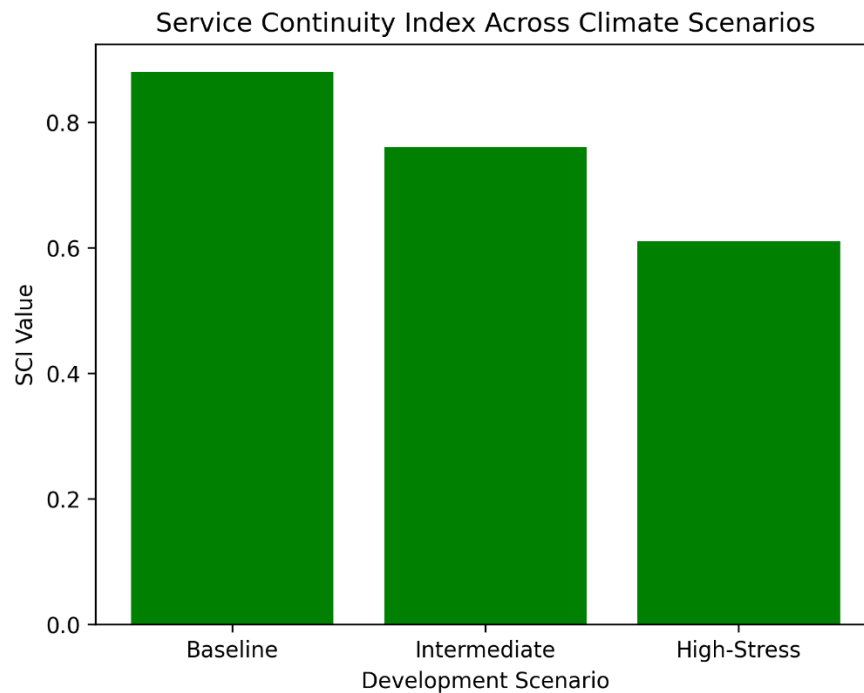


Figure 4. Service Continuity Index Across Climate Development Scenarios

The results presented in Figure 4 indicate that infrastructure systems designed using integrated nexus-based planning principles are more capable of maintaining operational service continuity under climate-adjusted demand conditions. Specifically, infrastructure investment strategies that account for energy–water dependency mechanisms demonstrate improved resilience performance relative to sectorally fragmented planning approaches.

### 3.5 Implications for Climate-Resilient Regional Infrastructure Planning

The simulation outcomes suggest that infrastructure planning within emerging tourism-oriented territorial systems must incorporate cross-sectoral resource management strategies to mitigate climate-induced infrastructure vulnerabilities. In the context of lake-based regional development, integrated nexus modelling offers a robust decision-support framework capable of aligning spatial development objectives with infrastructure sustainability imperatives.

Failure to account for infrastructure interdependencies may result in systemic performance degradation across regional service networks, particularly under high-demand growth trajectories combined with hydrological resource constraints. Consequently, regional planning institutions are encouraged to adopt nexus-oriented infrastructure investment strategies as a means of enhancing long-term infrastructure resilience under projected climate variability conditions.

### 3. Conclusion and Recommendations

This study has examined the application of an integrated Energy–Water–Transport (EWT) nexus modelling framework for climate-resilient regional infrastructure planning within the tourism-oriented territorial system of Lake Toba. The simulation results demonstrate that infrastructure systems operating under sectorally fragmented



planning approaches are increasingly vulnerable to climate-induced resource constraints, particularly in regions characterized by rapid spatial transformation and environmentally sensitive hydrological ecosystems.

The findings indicate that infrastructure performance stability declines significantly as tourism-driven demand growth interacts with climate variability stressors, including precipitation fluctuation and temperature anomalies. Under high-stress environmental scenarios, infrastructure service continuity was reduced by more than 25% relative to baseline operational conditions, primarily due to reciprocal dependencies between electricity generation processes and freshwater availability. This highlights the systemic nature of infrastructure vulnerabilities within lake-based regional development contexts, where energy production, water distribution, and mobility accessibility networks are functionally interdependent.

Furthermore, the Adaptive Capacity Index (ACI) results suggest that infrastructure resilience is strongly influenced by the extent to which planning frameworks account for cross-sectoral resource allocation dynamics. Infrastructure systems designed through integrated nexus-based planning mechanisms demonstrated improved operational continuity across long-term climate-adjusted development scenarios, thereby enhancing regional adaptive capacity under projected environmental uncertainty conditions.

## 4.2 Policy Implications

From a regional planning perspective, the outcomes of this study underscore the necessity of transitioning from conventional infrastructure investment strategies toward integrated planning frameworks capable of simultaneously addressing energy security, water resource sustainability, and transportation accessibility. In tourism-intensive territorial systems such as the Lake Toba development zone, infrastructure expansion policies that neglect inter-sectoral dependencies may inadvertently intensify resource competition and increase systemic service disruptions under future climate variability conditions.

Accordingly, several policy recommendations can be derived from the simulation findings:

### 1. **Integrated Infrastructure Planning Frameworks**

Regional planning authorities should adopt nexus-oriented infrastructure planning methodologies to improve coordination between electricity generation, freshwater distribution, and transport accessibility development initiatives.

### 2. **Climate-Responsive Infrastructure Investment**

Infrastructure investment strategies should incorporate climate-adjusted resource availability projections to mitigate hydrological stress impacts on energy production capacity and transport network reliability.

### 3. **Spatially Differentiated Service Allocation**

Infrastructure service provision should be aligned with spatial tourism demand clusters to reduce localized resource competition across lake-adjacent development corridors.

### 4. **Adaptive Infrastructure Governance**

Institutional mechanisms supporting cross-sectoral infrastructure management should be strengthened to enhance the resilience of interconnected service networks under environmental uncertainty.

The adoption of such policy measures may contribute to improving the long-term sustainability of regional infrastructure systems within climate-sensitive tourism development zones.



## Limitations and Future Research Directions

Despite the analytical contributions of the integrated EWT nexus modelling framework, this study is subject to several limitations. The simulation model does not incorporate real-time infrastructure operational data or socio-economic behavioural responses to infrastructure service disruptions. Future research may benefit from integrating agent-based modelling techniques and empirical infrastructure performance datasets to enhance predictive accuracy across spatial planning scenarios.

Additionally, further studies are recommended to examine the applicability of nexus-based infrastructure planning approaches in other lake-based or coastal tourism regions facing similar climate resilience challenges.

## Acknowledgment

The author would like to acknowledge the institutional support provided by regional spatial planning stakeholders involved in the sustainable infrastructure development initiatives within the Lake Toba territorial planning zone. The author also extends appreciation to infrastructure planning practitioners and environmental resource management experts whose policy insights have contributed to the conceptualization of integrated climate-resilient infrastructure modelling approaches applied in this study.

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